Lessons learned: Indoor Ultra-Wideband localization systems for an industrial IoT application

Swen Leugner* and Horst Hellbrück*†
*Lübeck University of Applied Sciences, Germany
Department of Electrical Engineering and Computer Science
Email: swen.leugner@fh-luebeck.de, hellbrueck@fh-luebeck.de
† University of Luebeck, Germany,
Institute of Telematics

***Abstract*—Since ultra-wideband (UWB) transceivers are available for wireless sensor networks, the usage in research and industry increased. Research efforts resulted in methods, measurement results, and solutions under laboratory conditions for a variety of indoor localization problems provided to the community. In this paper, we present an indoor positioning system (IPS) that is installed in a $1500\mathrm{m}^2$ real world production facility. In this real-world application, we faced some challenges that research has not addressed yet. For instance, challenges are receiving UWB signals from other floors in a multistory building through windows and multipath effects at walls like reflexions. We present solutions to increase the availability of such large-scale IPS, give a performance evaluation and recommendation for a modified NMEA sentence named iNMEA for IPS receivers.**

***Index Terms*—indoor positioning system, two-way-ranging, anchor, tag, multipath, ultra-wideband, indoor positioning testbed, increasing service availability**

I. Introduction

In recent years, interest in Indoor Positioning (IPS) is growing. Many scientific researchers and engineers in companies work on solutions for small area IPS; for instance, Schmitt et al. implemented [1] a reference system for indoor localization. The reference system is located on the university floor but limited to a corridor that has a length of approximately 100m. Their solution used a robot equipped with a camera system, which is not suitable for commercial indoor application due to privacy concerns. Tiemann et al. provided measurements from the ATLAS localization system [2]. The ATLAS localization system is based on the Time Difference of Arrival (TDoA) method. However, their experimental evaluation is performed in a small target area of less than $35\mathrm{m}^2$ without any obstacles in between. For our own evaluation, we installed an ultra-wideband IPS in a production facility, with the goal of tracking transport trolleys throughout the production process. Our IPS covers an area of $1500\mathrm{m}^2$. It is integrated into an industrial IoT application and to the best of our knowledge the largest of its kind in Germany. In this paper, we aim to share the experience and knowledge we gained throughout the planning, implementation, and installation of this large-scale IPS with the larger research community.

The paper is structured as follows: Section II provides an overview of the system design, components, and architecture. We describe our experience in Section III by presenting the challenges and solutions for large-scale localization systems. The paper concludes in Section IV with a short summary.

II. System Overview

In contrast to other research projects, we decided for a decentralized approach for implementation of the IPS. A decentralized approach means that the localization algorithm is executed on the IoT device, in our case a transport trolley, instead of the execution on a centralized localization server. Due to this decentralized approach, we benefit from shared resources and reduced complexity of the IPS. In Figure 1 we provide a system overview that illustrates the IPS and IoT application as well as the used technologies.

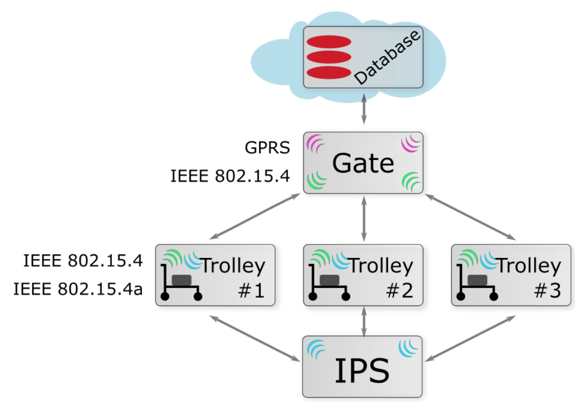

Fig. 1: Architecture of our industrial IoT application

The transport trolley utilizes two wireless sensor network standards: IEEE 802.15.4 and IEEE 802.15.4a. While the upper layers of the standards are similar, the main difference is the physical layer. IEEE 802.15.4 applies Offset-QPSK whereas IEEE 802.15.4a builds on ultra-wideband (UWB) technology. Because UWB signals are narrow in the time-domain, they are well-suited for measuring time of flight for IPS. For our indoor application, we deployed the well-known Decawave DW1000 UWB transceiver which measures timestamps with a resolution of 15.65 ps. The UWB transceiver performs localization whereas the IEEE 802.15.4 transceiver is used for the IoT communication. In our IoT application, the sensor node on the transport trolley wakes up every 5

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TABLE I: Comparison of NMEA and iNMEA

Name in NMEA	Example	NMEA	iNMEA
Sentence ID	$GPGGA	GNSS Fix Data	IPS Data
Time	180834	18:20:11	Reserved for later use
Latitude	402.89, N	4d 2.89' N	x = 402.89 m
Longitude	81.76, W	8d 176' W	y = 81.76 m
Fix Quality {0,1,2}	1	0 - invalid 1 - GPS fix 2 - DGPS fix	0 - invalid 1 - 1st floor 2 - 2nd floor
Number of Satellites	04	4 Satellites in View	4 anchors used for result
HDOP	1.5	Horizontal accuracy	Reserved for later use
Altitude	370.0,M	370.0 Meters over ground	Encoded unique anchor IDs
Height of geoid	-14.0 M	-14.0 meters	Reserved for later use
Time since last DGPS update	103	Age of DGPS data	Time until position result [ms]
DGPS reference station id	200	Differential Station 200	Reserved for later use
Checksum	*13	Check for tx errors	Check for tx errors

minutes and initiates the localization process by switching on microcontroller board with the DW1000 transceiver. The sensor node shuts down the power supply of the microcontroller board after 10s independent of the status of the localization process. During the localization process, distances between anchor and the sensor node on the trolley are estimated by a two-way-ranging (TWR) algorithm. We apply the TriClock [3] algorithm to compensate for clock drift during the ranging. If the position is successfully calculated, the IPS microcontroller sends an iNMEA string via USART to the application microcontroller. The application microcontroller adds additional sensor data and transmits a frame to the IEEE 802.15.4 gateway. Finally, the gateway forwards the message to the database of a cloud service, see Figure 1.

A. iNMEA

We designed our IPS for easy and seamless integration into existing IoT platforms. Therefore, we deployed a derivate of NMEA 0183-HS protocol between the application and IPS microcontrollers on the transport trolley. NMEA 0183-HS is widely used in Global Navigation Satellite Systems (GNSS) and is commonly supported by IoT platforms. For our purpose, we adopted the Global Positioning System Fix Data (GPGGA) sentence code and named it Indoor NMEA (iNMEA) to account for our changes to the NMEA sentence. Table I compares the message fields of NMEA and iNMEA.

Our main modification to NMEA was changing the geographic coordinates used by GNSS to cartesian coordinates that are referenced to a fixed point in the area where the IPS is deployed. Secondarily, we included additional diagnostic data in the protocol. The *Time until Position* provides the time for localization. This time increases in situations where non-optimal anchor configurations were chosen, too few anchors can be reached or many collisions occured during media access. The *Encoded Anchor IDs* records the specific anchors that were used in the localization algorithm, which helps to diagnose wrong anchor positions and identify multipath propagation. Due to our positive experience, we recommend the iNMEA protocol for future highly integrated IPS services.

III. Challenges and Solutions

During deployment and tests some challenges occured that were not addressed by research and industry.

First, a significant difference compared to state of the art system and a challenge by itself is that the sensor node on the transport trolley regularly shuts down the IPS microcontroller for several minutes in our application. Hence, on every power up, the transport trolley could have moved in the production site and information about anchors e.g. might be completely outdated. We addressed the problem of finding anchors by sending periodic beacons by each anchor with a period of 1s. Each beacon includes the absolute position of the anchor in three dimensions and the anchor's unique identification number. When switched on, the IPS microcontroller on the transport trolley first listens for n seconds for beacons. After that, it starts ranging and calculates distance to each anchor.

Secondly, due to shadowing effects, the average range was 15m or less in the production facility. This is less than 40% of the typical communication range measured by others [4], [5]. The short communication range required many anchors that we had to install. In the end, we deployed 44 anchors to cover the target area. In a second step after evaluation of the system we solved the problem partially by increasing the transmission power level of the DW1000. However, this approach need careful consideration as raising the power results in a higher spectral emission in the communication channel. Such a solution might exceed regulatory limits, depending on the region.

Third, another issue with the increasing transmission power is that multipath effects occur more frequently. Indeed, by increasing the power, the DW1000 received beacons from anchors placed on other floors. We were able to filter out beacons originating from different floors in two steps. First, we added a floor identifier field to each beacon and utilized NMEA's fix quality to encode the floor level (see Table I). Then, we applied an algorithm that decided on the floor based on the received signal strength of beacons. We select the floor according to the strongest received beacon signal and ignored all anchors from other floors in the following. However, intra-floor multipath effects occured, i.e. ranging errors due to non-line-of-sight connections and signal reflection on the walls. To solve this problem, we used a new localization algorithm called mRansac [6].

Fourth, the last problem we had to solve were anchor geometries that produce erroneous results according to the topology of the anchors. In order to rate topologies we introduce a metric called horizontal dilution of precision (HDOP) that is calculated based on the anchor positions and the estimated position which is used to rate solution for the mRansac algorithm.

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A. Performance Evaluation

In this subsection, we provide results of performance measurements collected with early and final software incl. configuration of the IPS. These performance measurements were collected with the help of our iNMEA protocol during the operation of the IPS in the production. A key performance indicator for localization is success rate of the localization process. In the first version in 2017 we reached 80% within a period of 28 days, see Figure 2. In our application we aim for a production optimization according to lean production philosophy, therefore the success rate needs to be close to 100%.

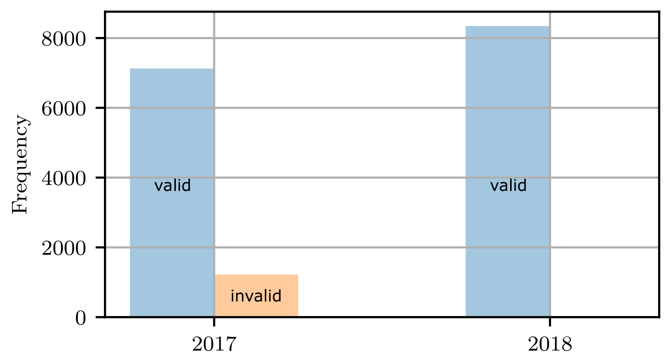

Fig. 2: Comparison of valid position flag of iNMEA in 2017 and 2018

Due to our efforts described in Section III, the success rate of our IPS service increased to 100%. In the version of 2017 quite often only beacons from 3 anchors were received, see Figure 3. 3 anchors are not always enough to calculate a valid position. If anchors are aligned in a line, the algorithm will not be able to calculate a valid position. In the version of 2018, in most cases we reached more than 10 anchors and therefore had a variety of selection of anchors to find a valid position.

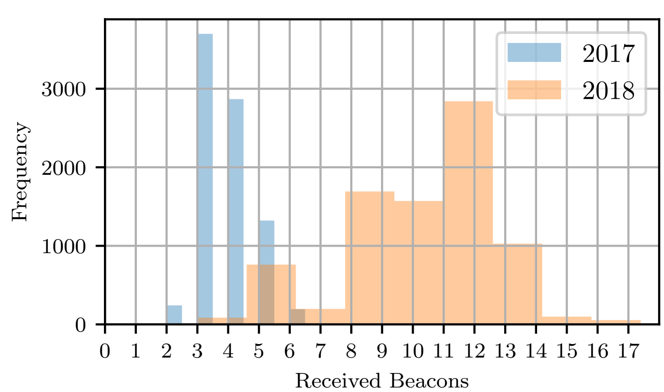

Fig. 3: Number of received Beacons

IV. Conclusion

In this paper, we showed that a large-scale indoor positioning system provides a variety of challenges. We identified effects for large-scale and real-world deployments which are not accounted for in existing work e.g. multipath propagation. We drew attention to balance UWB communication range for a reasonable number of anchors and to avoid multipath. Additionally, we recommended the use of iNMEA as a communication protocol between the IPS and application microcontrollers. Finally, we showed how to increase the availability of an IPS service in large-scale positioning systems.

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